NUCLEOSYNTHESIS OF R-PROCESS ELEMENTS BY JITTERING JETS IN CORE-COLLAPSE SUPERNOVAE

Oded Papish[1] and Noam Soker[1]

ABSTRACT

We calculate the nucleosynthesis inside the hot bubble formed in the jittering-jets model for core collapse supernovae (CCSNe) explosions, and find the formation of several$\times 10^{-4} M_\odot$ of r-process elements. In the jittering-jets model fast jets launched from a stochastic accretion disk around the newly formed neutron star are shocked at several thousands km, and form hot high-pressure bubbles. These bubbles merge to form a large bubble that explode the star. In the current study we assume a spherically symmetric homogenous bubble, and follow its evolution for about one second during which nuclear reactions take place. The jets last for about one second, their velocity is $v_j = 0.5c$, and their total energy is $\sim 10^{51}$ erg. We use jets' neutron enrichment independent on time, and follow the nuclear reactions to the formation of the seed nuclei up to $Z \leq 50$, on which more neutrons will be absorbed to form the r-process elements. Based on the mass of the seed nuclei we find the r-process element mass in our idealized model to be several$\times 10^{-4} M_\odot$, which is slightly larger than the value deduced from observations. More realistic calculations that relax the assumptions of a homogenous bubble and constant jets composition might lead to agreement with observations.

1. INTRODUCTION

The mechanism for the explosion of core-collapse (CC) supernovae (SNe) is still unknown. Most popular are models based on explosion driven by neutrinos. Less popular are models based on jet-driven explosions. (e.g. LeBlanc & Wilson 1970; Meier et al. 1976; Bisnovatyi-Kogan et al. 1976; Khokhlov et al. 1999; MacFadyen et al. 2001; Höflich et al. 2001; Fargion 2003; Woosley & Janka 2005; Couch et al. 2009, 2011; Lazzati et al. 2011). Recent observations (e.g., Wang et al. 2001; Leonard et al. 2001, 2006; Elmhamdi et al. 2003;

[1]Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel; papish@physics.technion.ac.il; soker@physics.technion.ac.il

Chugai et al. 2005; Smith et al. 2011) that found asymmetry in CCSNe suggest that jets might indeed play an important role in at least some CCSNe.

In neutrino-driven models where jets play no role at all (e.g. Bethe 1990; Nordhaus et al. 2010; Brandt et al. 2011; Hanke et al. 2011), the neutrinos are absorbed near the stalled-shock at ~ 300 km, and revive the shock. Namely, they eject the material in that region. In some theoretical studied the jets were injected at large distances beyond the stalled-shock radius (e.g., Khokhlov et al. 1999; Höflich et al. 2001; Maeda & Nomoto 2003; Couch et al. 2009, 2011). Höflich et al. 2001 injected slow and fast jets at a radius of 1200 km in a helium star for about two seconds. They show the possibility of exploding the star with slow jets. Their results show that the polarization in SN199em is consistent with slow jets. In model m2r1hot of Couch et al. 2011 a jet was injected near the speed of sound, leading to the formation of a hot bubble. In others, like MacFadyen et al. (2001), the jets were injected much closer to the neutron star (NS), at 50 km. In the simulations of MacFadyen et al. (2001) the jets were injected at a much later time in the explosion, and are less relevant to our goal of exploding a star with jets. Kohri et al. (2005) propose that disk-wind energy is able to revive a stalled shock and help to produce a successful supernova explosion.

Our *jittering-jet model* for explosion (Soker 2010; Papish & Soker 2011, hereafter Paper 1) is based on the following points, that differ in several ingredients from the models cited above (for more detail see Paper 1). (1) We don't try to revive the stalled shock. To the contrary. Our model requires the material near the stalled-shock to fall inward and form an accretion disk around the newly born NS or black hole (BH). (2) We conjecture that due to stochastic processes and the stationary accretion shock instability (SASI; e.g. Blondin & Mezzacappa 2007) segments of the post-shock accreted gas (inward to the stalled shock wave) possess local angular momentum. When they accreted they form and accretion disk with rapidly varying axis direction. (3) We assume that the accretion disk launches two opposite jets. Due to the rapid change in the disk's axis, the jets can be intermittent and their direction rapidly varying. These are termed jittering jets. (4) We show in Paper 1 that the jets penetrate the infalling gas up to a distance of few$\times$1000 km, i.e., beyond the stalled-shock. However, beyond few$\times$1000 km the jets cannot penetrate the gas any more because of their jittering. The jittering jets don't have the time to drill a hole through the ambient gas before their direction changes; they are shocked before penetrating through the ambient gas. This condition can be met if the jets' axis rapidly changes its direction. This process of depositing jets' energy into the ambient medium to prevent further accretion is termed the *penetrating jet feedback mechanism.* (5) The jets deposit their energy inside the star via shock waves, and form two hot bubbles, that eventually merge and accelerate the rest of the star and lead to the explosion. In section 2 below we use self similar calculations to further explore this process. (6) The jets are launched only in the last phase of accretion

onto the NS. For the required energy the jets must be launched from the very inner region of the accretion disk.

Nucleosynthesis can occurs in the expanding jets (or disk winds) and in the postshock region. Previous studies include Cameron (2001) who discussed the nucleosynthesis inside jets launched at a velocity of $0.5c$ from an accretion disk around a rapidly rotating proto NS. He suggested the possibility of creating r-process elements inside the jets. Nishimura et al. (2006) simulated the r-process nucleosynthesis during a jet powered explosion. In their simulation a rotating star with a magnetic field induces a jetlike outflow during the collapse which explode the star. Neutrinos play no role in the simulation. Unlike their model, our model does not have a large scale rotation of the star, and the jets penetrate farther away creating hot bubbles.

In our jittering-jets explosion model the jets are launched close to the NS where the gas is neutron-rich (e.g., Kohri et al. 2005). In section 3 we examine the implications of this on the nuclear reactions (nucleosynthesis) in the inflated hot bubble. The properties of the bubbles are as derived in section 2. Our discussion and summary are in section 4.

2. DYNAMICAL EVOLUTION OF THE INFLATED BUBBLES

In this section we describe an approximate model for the inflated bubbles and their dynamical evolution. The analysis here is similar to that conducted by Volk & Kwok (1985) to study the evolution of the spherical hot bubble in planetary nebulae. During the active phase of the jets we derive a self-similar analytical solution to the gas-dynamical equations. At later times the solution is numerical.

The jittering jets form wide bubbles that occupy most of the volume up to the distance they have reached; eventually the bubbles merge (see Paper 1). Our basic assumption is therefore that the two inflated bubbles merge to form one large bubble. The low density high energy volume inside R_s is termed hereafter the 'spherical bubble'. If we equate the volume of the assumed spherical bubble with the total volume of the wide inflated bubbles, the radius of the spherical bubble R_s is only slightly smaller that the distance the inflated bubbles have reached. This assumption leads to a spherically symmetric flow that allows a self similar solution for constant power jets. We also assume that the gas inside the bubble is homogeneous, i.e., the composition, density, and pressure are constant inside the bubble. The energy of the jets injected into the bubble with a power of $\dot{E}_j$ forces the bubble to expand. The expanding spherical bubble pushes the dense surrounding gas supersonically outward, forming a forward shock ahead of this dense shell. The boundary of the dense

shell and the bubble is a contact discontinuity, across which the pressure is constant but not the density or the composition. This flow structure is drawn schematically in Fig. 1. The mass M_s in the shell is the swept-up ambient gas. As the dense shell is thin, we take the radius of the forward shock to be equal to the radius of the contact discontinuity (which is the radius of the spherical bubble) R_s. The pre-shock (up-stream) ambient density profile at radius $r > R_s$, is taken to be a power law, with the scaling from Wilson et al. (1986) and Mikami et al. (2008) (see Paper 1)

$$\rho_s(r) = Ar^\beta = 1.3 \times 10^{10} \left(\frac{r}{100 \text{ km}}\right)^{-2.7} \text{ g cm}^{-3}, \quad 30 \lesssim \text{r} \lesssim 10^4 \text{ km}. \tag{1}$$

The spherical flow obeys the following conservation equations (Volk & Kwok 1985)

$$\frac{dM_s}{dt} = 4\pi R_s^2 \rho(R_s)\dot{R}_s, \tag{2}$$

$$\frac{d}{dt}\left(M_s\dot{R}_s\right) = 4\pi R_s^2 P\dot{R}_s, \tag{3}$$

$$\frac{d}{dt}\left(4\pi R_s^3 P\right) = \dot{E}_j - 4\pi R_s^2 P\dot{R}_s, \tag{4}$$

where P is the pressure inside the bubble. Equations (2) - (4) describe the conservation of mass, momentum, and energy respectively. The energy inside the bubble includes the

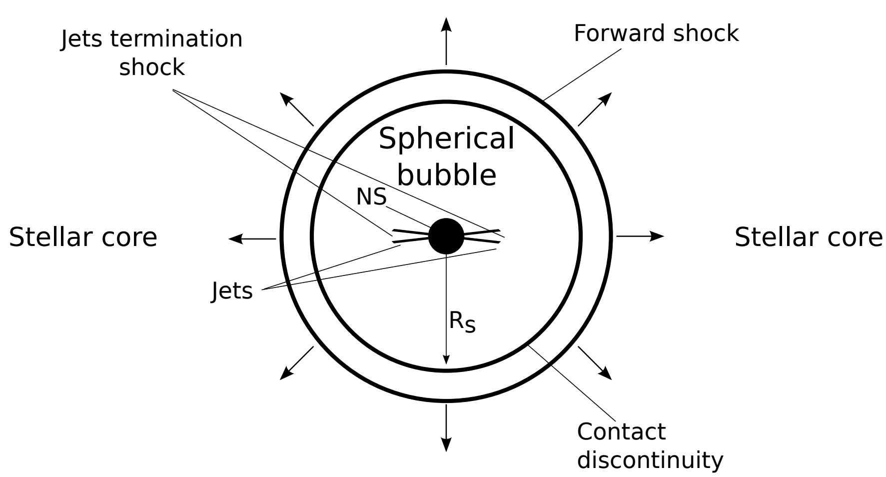

Fig. 1.—: Schematic drawing of the inflated spherical bubble. The spherical bubble is powered by jittering jets, i.e., they change their direction at a high rate, launched from an accretion disk around the newly formed neutron star. This spherical bubble explodes the star according to our model. R-process elements are fused inside the bubble. The typical radius during the jets' active phase is 3000-10000 km.

thermal energy of the gas and the radiation energy. We neglect losses by neutrinos (see Paper 1) and energy production and sink from nuclear reactions.

During the active time period of the jets the solution to equations (2) - (4) is a self-similar solution, which we take in the form

$$R_s(t) = R_0 t^{\alpha}. \tag{5}$$

Using equations (2) - (4) we get the following parameters

$$\alpha = \frac{3}{\beta+5}, \quad R_0^{\beta+5} = \frac{(\beta+3)(\beta+5)^3}{12\pi A(2\beta+7)(\beta+8)}\dot{E}_j. \tag{6}$$

A short time of ~ 0.1 s after the jets launching process ceases, energy injection to the bubble ends. The time delay comes from the jets' crossing time from the NS to the bubble. At that moment the self-similar solution no longer holds, and we need to turn to a numerical solution.

The jets' are assumed to be injected at $r \sim 15$ km for a time period of $t_s = 1-2$ s. Here we take the velocity of the jets to be $150,000$ km s^{-1} (Cameron 2001). This velocity is larger than the velocity used in Paper 1 as it better fits the escape velocity from the surface of the newly formed NS. The velocity is chosen to be the escape velocity from the neutron star, as we are interested in the jets emerging from the neutron star vicinity. Some studies inject the jets at distances of > 1000 km at lower velocities, e.g Couch et al. (2011), while others use relativistic jets, e.g., Lazzati et al. (2011), who inject the jets at 10^4 km within several seconds. The total mass carried by the two jets is either $0.006M_{\odot}$ or $0.0036M_{\odot}$, corresponding to a total injected energy of $E = 1.7\times10^{51}$ erg or $E = 1.0\times10^{51}$ erg respectively. For the parameters of $\dot{E} = 1.7\times10^{51}$ erg s^{-1} , and active phase time of $t_s = 1$ s, for example, the solution during the jets' active phase is

$$R_s(t) = 6.6\times10^8\, t^{1.3}\ \mathrm{cm}, \quad 0 < \mathrm{t} < \mathrm{t_s} = 1\ \mathrm{s}. \tag{7}$$

For later times we numerically integrate equations (2) - (4) with $\dot{E}_j = 0$, and using the the results of the self similar solution at $t = t_s$ as initial conditions. For a check, we also numerically integrate the equations for the full time of the solution. The numerical solution coincides with the self-similar solution after a very short time. The full numerical solution for three cases are shown in Fig. 2. The plot shows the radius R_s, temperature T, density ρ, and entropy s of the bubble as a function of time. The parameters for the three cases are given in the figure caption. The jets' power was taken to be a constant for $0 < t < t_s$, and $\dot{E} = 0$ for later times. This gives the little bump at $t = t_s$ in the graph.

The two cases differ by jets' power and having active time of $t_s = 1$ s, are similar in their general behavior. As well, changing the active phase duration from $t_s = 1$ s to $t_s = 2$ s

does not make large differences in the dynamical properties (the extra density line in the left panel of fig. 2.). All cases lead to explosion. Later we will show that these cases are different in nucleosynthesis outcomes.

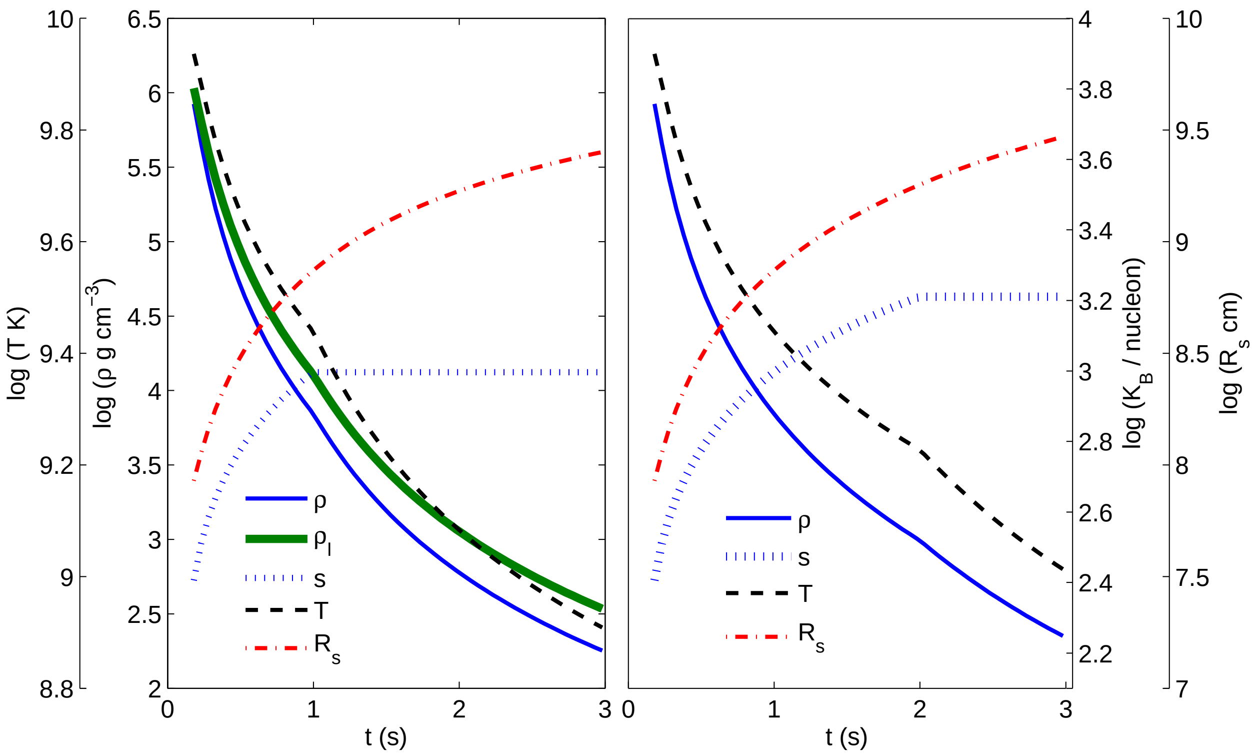

Fig. 2.—: Left: Radius R_s, Temperature T, density ρ, and entropy s of the spherical bubble as a function of time for the model with jets' power of $\dot{E} = 1.7 \times 10^{51}$ erg s^{-1} and a jets' active phase lasting $t_s = 1$ s. ρ_l is the density for a case with $\dot{E}_j = 1 \times 10^{51}$ erg s^{-1} for the same duration of $T_s = 1$ s. Right: the same but for a model with $\dot{E} = 0.85 \times 10^{51}$ erg s^{-1} and an active phase duration of $t_s = 2$ s

For the typical parameters expected in the model the main results of this section are as follows. (1) The spherical bubble reaches a typical radius of $\sim 10^4$ km at the end of the jets' active phase. (2) The temperature relevant for nucleosynthesis ($T \sim 3 \times 10^9$ K) occurs at about one seconds from the beginning of the jet injection. (3) The density in the bubble of $\sim 10^4$ g cm^{-3} at that time implies that nuclear reactions will be of a high enough rate to be significant. For that, in the next section we study the nucleosynthesis inside the bubble.

3. NUCLEOSYNTHESIS INSIDE THE BUBBLE

In the previous section we found the temperature inside the bubble to start at $\sim 10^{10}$ K, and to decrease due to adiabatic cooling to 2.5×10^9 K in ~ 1 s. The relevant nuclear reactions inside the hot bubble start when the temperature is about $T \simeq 9 \times 10^9$ K and stop at $T \simeq 2.5 \times 10^9$ K. During this time fresh material is injected into the bubble from the jets. As the jets are launched from very close to the neutron star, they are composed of highly enriched neutron material (Kohri et al. 2005). During the expansion of the jets they adiabatically cool, and nucleons might fuse to give α particles and heavier nuclei (e.g., Cameron 2001; Maeda & Nomoto 2003; Fujimoto et al. 2008). However, the jets are eventually shocked with a post shock temperature of $> 10^{10}$ K. At that temperature all nuclei rapidly disintegrate, and a gas composed of free nucleons is formed. Our nucleosynthesis calculations start from the free-nucleons post shock jets' gas. At $t \simeq 0.2$ s when the temperature inside the spherical bubble has dropped to $T \simeq 9 \times 10^9$ K, the free nucleons fusion rate overcomes the disintegration rate and α particles start to be accumulated. During the time up to ~ 1 s the temperature drops further and α particle fuse to form heavier nuclei until α freeze-out is reached.

The nuclear reaction network is similar to that given in Woosley & Hoffman (1992). The reaction rates are taken from the JINA Reaclib Database (Cyburt et al. 2010), and include reactions with 1,2, and 3 body interactions and beta decays. The reaction network is integrated assuming a uniform composition in the bubble and a continues injection of protons and neutrons from the jets until the jets terminated. For the electron fraction Y_e we use values for the accretion disk around a neutron star as calculated by Kohri et al. (2005). For parameters relevant to our model we find from the calculations of Kohri et al. (2005) that the neutron to proton ratio is in the range $n/p \simeq 5-10$, namely, $Y_e \simeq 0.09-0.17$. Here we integrate the reaction network for 3 different electron fractions $Y_e = 0.09, 0.17, 0.25$. This correspond to a neutron to proton ratio of $n/p = 10, 5$, and 3. We study nucleosynthesis for jets' active phase of 1 s and 2 s. The network is solved independently of the hydrodynamics solution of section 2 (Hix & Thielemann 1999).

The nucleosynthesis results are summarized in Fig. 3. The plots show the mass fraction of neutrons ,α particles, and of total seed elements during the evolution of the bubble. By seed elements we refer to nuclei on which further neutron capture will occur to synthesis the r-process nuclei (Woosley & Hoffman 1992; Witti et al. 1994). The inclusion of all nuclear processes beyond the seed nuclei is beyond the scope of the present paper. They will be studied in a forthcoming paper where a full multi-dimensional gasdynamical code will be used to study the interaction of the jets with the core material.

We assume that the post-shock freshly injected jets' material is fully mixed inside the

bubble. This is based on the expected formation of vortices inside the bubble by the jittering jets. The post-shock velocity for $\gamma = 4/3$ is $\sim 20,000$ km s^{-1}, and for a bubble's radius of $R_s \simeq 7000$ km the mixing time is ~ 0.3 s. This shows that the assumption is reasonable, but that mixing is not complete. The assumption of full mixing will be relaxed in the future with full multi-dimensional numerical simulations. Since the post-shock entropy increases as the jets are shocked at larger distances (because the density is lower), the entropy inside the bubble increase as long as we inject fresh jets' material. At the relevant time of nucleosynthesis the entropy per nucleon reaches values of > 100 $\mathrm{K_B}$/nucleon as is required for r-process elements production (Hoffman et al. 1997). Our flow structure differs from calculations where there is no mixing and the entropy is almost constant during nucleosynthesis (e.g. Witti et al. 1994; Woosley et al. 1994; Arcones et al. 2007; Kuroda et al. 2008).

As well, the continuous injection of nucleons as nucleosynthesis takes place reduces the final mass of seed nuclei. This is seen by comparing the mass fraction of seed nuclei for the two simulated cases, of 1 s and 2 s jets active phase duration (Table 1 and Fig. 3). The table shows also the sensitivity of the nucleosynthesis production to the value Y_e assumed at the base of the jet.

	Model I			Model II			Model III		
Total mass	0.60	0.60	0.60	0.36	0.36	0.36	0.60	0.60	0.60
Power	1.7	1.7	1.7	1.0	1.0	1.0	0.85	0.85	0.85
Y_e	0.09	0.17	0.25	0.09	0.17	0.25	0.09	0.17	0.25
n	79%	60%	42%	79%	60%	42%	81%	63%	46%
α	8%	14%	21%	8%	14%	20%	14%	24%	33%
Seed	13%	25%	36%	13%	25%	37%	4%	10%	17%

Table 1:: Mass fraction of neutrons, α particles and seed elements for different electron fractions Y_e. Models I and II are for jets with a duration of $t_s = 1$ s. Model III is for jets with a duration of $t_s = 2$ s. Total mass is in units of $10^{-2} M_\odot$. Power is in units of 10^{51} erg.

The most likely case is for jets' active phase of $1 - 2$ seconds, although the jets' power might vary with time (e.g. Höflich et al. 2001; Couch et al. 2009). The electron fraction is likely to be in the lower part of the range $Y_e = 0.09 - 0.17$, corresponding to a neutron to proton ratio of $n/p = 5 - 10$ (Kohri et al. 2005). Also, the total energy might be slightly less that 1.7×10^{51} erg used here. From those values we find the seed nuclei mass fraction to be $0.02 - 0.2$, and the corresponding total seed nuclei mass to be $10^{-4} - 10^{-3} M_\odot$, with

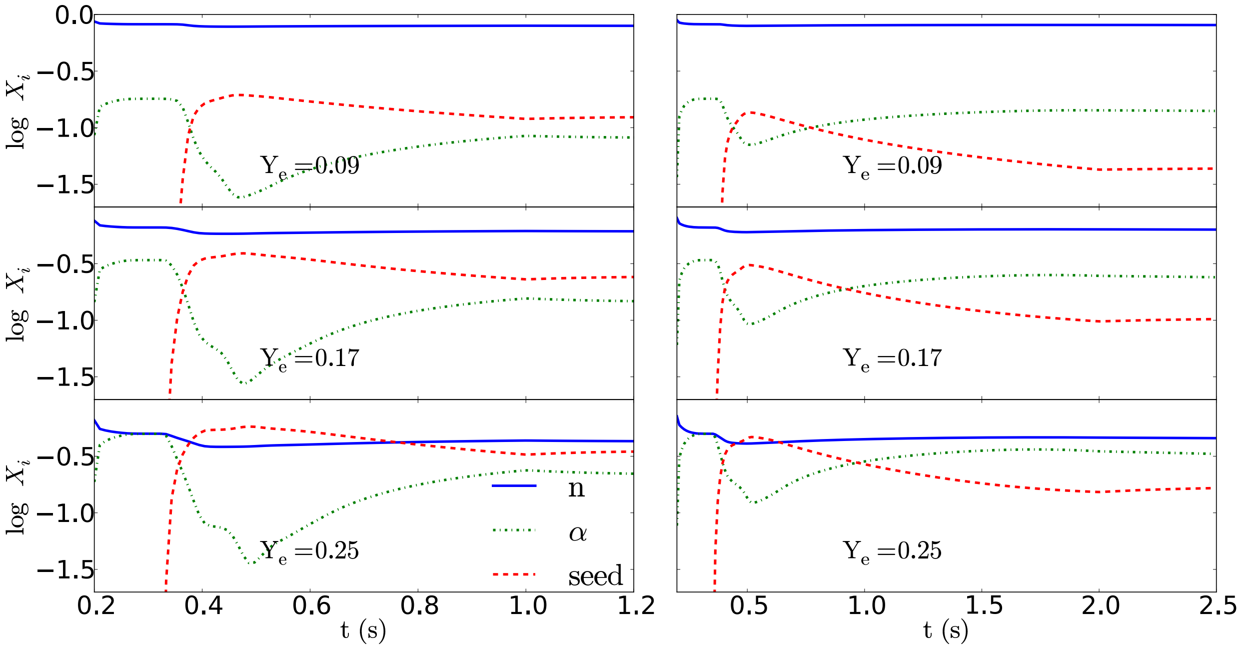

Fig. 3.—: Evolution of the mass fraction of neutrons, α particles, and seed nuclei for the r-process. Left: Model I with $t_s = 1$ s and power of $\dot{E} = 1.7 \times 10^{51}$ erg. Right: Model III with $t_s = 2$ s and power of $\dot{E} = 0.85 \times 10^{51}$ erg. In each panel the initial ratio of electron to nucleon Y_e is given. The total mass is $0.006 M_{\odot}$ for both cases.

more likely values in the range $10^{-4} - 3 \times 10^{-4} M_{\odot}$. After neutrons are absorbed (beyond the scope of this paper) and form the r-process elements, the total mass of the r-process elements is $2 - 3$ times that of the seed nuclei. This gives that the expected mass of the r-process elements in our jittering-jets explosion model is $\sim$ several $\times 10^{-4} M_{\odot}$.

¿From the solar abundance Mathews & Cowan (1990) deduced that the average mass of r-process material ejected in a CCSN is $\approx 10^{-4} M_{\odot}$. Our simple and idealized model overproduces r-process elements, but not by much. In future 3D numerical simulations three assumptions that have been used here will be relaxed. These might reduce the production of r-process elements by a factor of $\sim 3 - 5$. (1) Simulating precessing jets will cause deviation from sphericity. We expect that in some regions the production of r-process elements will be less efficient. (2) Adding the mass at the termination shocks of the jets will result in an inhomogeneous bubble. Basically, the flow will differ by having regions where the matter cools adiabatically with no addition of entropy (low entropy regions), and regions of high entropy where gas is added. This might lead to less efficient production of r-process elements in some regions. (3) We will change the the neutron enrichment (or Y_e) of the jets with time. It is quite possible that at early times the jets are less neutron enriched than at later time when the accretion disk is depleted and more mass comes from closer to the NS.

4. SUMMARY

Our main goal was to examine the nucleosynthesis inside the bubbles formed by the jets in the the *jittering-jets model* for core collapse SN explosion (Paper 1). The two jets are launched from an unrelaxed accretion disk around the newly formed NS. Because of stochastic accretion of mass and angular momentum the disk's axis is rapidly changing and the disk might even be intermittent. The jets penetrate to a distance of few $\times$ 1000 km through the infalling stellar core. However, because of their changing direction they cannot penetrate beyond that distance. The jets are shocked and form hot low-density bubbles. These high pressure bubbles explode the star. This process where the non-penetrating jets prevent further accretion to the center (a negative feedback) is termed the *penetrating jet feedback mechanism.*

To facilitate a solution in the scope of the present paper we assumed that the bubbles formed by the two jittering jets merge to form one large spherical bubble, as shown schematically in Fig. 1. The spherical solution under these assumptions is composed of two phases. In the first one, the jets' active phase, energy and mass are injected into the bubble at constant rates. The second phase starts when the jets' cease, and the bubble starts to expand adiabatically. The gasdynamical equations in spherical symmetry were solved analytically using a self-similar solution for the jets' active phase, and numerically thereafter (section 2).

Beyond the assumptions of jittering jets that have the power to explode the star and the formation of a spherical bubble, all quantitative parameters have been used before by some studies. We did not adjust or played with any quantitative parameter in the solutions presented here. (1) The jets' total energy of $1-1.7\times10^{51}$ erg is taken from the energy required to explode CCSNe. (2) The jets' velocity of $v_j = 0.5c$ comes from the escape velocity near the NS surface. This value for jets' velocity from NS has been used before, e.g., Cameron (2001). (3) The energy and velocity determine the total mass carried by the jets. (4) The $\sim 1-2$ seconds duration of the jets' active phase is similar to durations assumed in other studies, e.g. Höflich et al. (2001); Couch et al. (2009). (5) The ambient density profile (eq. 1) is taken from Wilson et al. (1986) and Mikami et al. (2008). (6) The neutron fraction (or electron fraction Y_e) of the jets' material is taken from the calculation of Kohri et al. (2005).

The assumption of a spherical bubble that has the energy to explode the star and the quantitative parameters listed above determine the properties and evolution of the bubble. From these we calculated the nucleosynthesis inside the bubble. In the limited scope of the present paper we numerically integrated a reaction network that follows the fusion up to the seed nuclei with $Z \leq 50$. The results of the nucleosynthesis calculations for the three studied cases are presented in Table 1 and Fig. 3. We note that Ye = 0:25 is above the expected value during the main phase of the jets (Kohri et al. 2005), but might be applicable at early

time before the NS is fully relaxed by neutrino cooling.

During the integration of the network an α freeze-out is reached, i.e., when the number of α particles does not change anymore. We take the heavy nuclei from the α freeze-out to be the seed elements for r-process elements. From the mass of seed elements for the typical parameters expected in this study, $Y_e = 0.1$, energy of 10^{51} erg, and active jets' duration of $t_s \simeq 1-2$ s, we estimate the total mass of the fused r-process elements to be several $\times 10^{-4} M_\odot$. This is a few times larger than $\approx 10^{-4} M_\odot$, the average mass of r-process elements per CCSN deduced from observations (Mathews & Cowan 1990). We note that in many observed cases the production of r-process elements is much below the average (e.g., Sneden et al. 2010 and references therein). It is possible, therefore, that the conditions used here are met only in a fraction of CCSNe. For example, in some cases the value of Y_e at the base of the jets is larger than used here, namely $Y_e \gtrsim 0.3$, where the number of neutrons is not sufficient to produce r-process elements.

One strong assumption of the present work is that the bubble is homogeneous in temperature and composition. This assumption will be relaxed in a future study when the gas-dynamical equations will be solved with a multi-dimensional numerical code. The accurate treatment of the inflation process of the bubble will justify the inclusion of a more extended nuclear reaction network. Nevertheless, our results here strongly suggest that within the context of the *jittering-jets model* for core collapse SN explosions, the nucleosynthesis of the r-process elements is a a likely possibility. This outcome strengthen the possibility that CCSNe are driven by jets.

We thank an anonymous referee for helpful comments. This research was supported by the Asher Fund for Space Research at the Technion and the Israel Science foundation.

REFERENCES

Arcones, A., Janka, H.-T., & Scheck, L. 2007, A&A, 467, 1227

Arnould, M., Goriely, S., & Takahashi, K. 2007, Phys. Rep., 450, 97

Bethe, H. A. 1990, Reviews of Modern Physics, 62, 801

Bisnovatyi-Kogan, G. S., Popov, I. P., & Samokhin, A. A. 1976, Ap&SS, 41, 287

Blondin, J. M., & Mezzacappa, A. 2007, Nature, 445, 58

Brandt, T. D., Burrows, A., Ott, C. D., & Livne, E. 2011, ApJ, 728, 8

Cameron, A. G. W. 2001, ApJ, 562, 456

Chugai, N. N., Fabrika, S. N., Sholukhova, O. N., et al. 2005, Astronomy Letters, 31, 792

Couch, S. M., Wheeler, J. C., & Milosavljević, M. 2009, ApJ, 696, 953

Couch, S. M., Pooley, D., Wheeler, J. C., & Milosavljević, M. 2011, ApJ, 727, 104

Cyburt, R. H., et al. 2010, ApJS, 189, 240

Elmhamdi, A., Danziger, I. J., Chugai, N., et al. 2003, MNRAS, 338, 939

Fargion, D. 2003, Chinese Journal of Astronomy and Astrophysics Supplement, 3, 472

Fujimoto, S.-i., Nishimura, N., & Hashimoto, M.-a. 2008, ApJ, 680, 1350

Hanke, F., Marek, A., Mueller, B., & Janka, H.-T. 2011, arXiv:1108.4355

Hix, W. R., & Thielemann, F.-K. 1999, Journal of Computational and Applied Mathematics, 109, 321

Hoffman, R. D., Woosley, S. E., & Qian, Y.-Z. 1997, ApJ, 482, 951

Höflich, P., Khokhlov, A., & Wang, L. 2001, 20th Texas Symposium on relativistic astrophysics, 586, 459

Khokhlov, A. M., Höflich, P. A., Oran, E. S., et al. 1999, ApJ, 524, L107

Kohri, K., Narayan, R., & Piran, T. 2005, ApJ, 629, 341

Kuroda, T., Wanajo, S., & Nomoto, K. 2008, ApJ, 672, 1068

Lazzati, D., Morsony, B. J., Blackwell, C. H., & Begelman, M. C. 2011, arXiv:1111.0970

LeBlanc, J. M., & Wilson, J. R. 1970, ApJ, 161, 541

Leonard, D. C., Filippenko, A. V., Ardila, D. R., & Brotherton, M. S. 2001, ApJ, 553, 861

Leonard, D. C., Filippenko, A. V., Ganeshalingam, M., et al. 2006, Nature, 440, 505

MacFadyen, A. I., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 410

Maeda, K., & Nomoto, K. 2003, ApJ, 598, 1163

Mathews, G. J., & Cowan, J. J. 1990, Nature, 345, 491

Meier, D. L., Epstein, R. I., Arnett, W. D., & Schramm, D. N. 1976, ApJ, 204, 869

Mikami, H., Sato, Y., Matsumoto, T., & Hanawa, T. 2008, ApJ, 683, 357

Nishimura, S., Kotake, K., Hashimoto, M.-a., Yamada, S., Nishimura, N., Fujimoto, S., & Sato, K. 2006, ApJ, 642, 410

Nordhaus, J., Burrows, A., Almgren, A., & Bell, J. 2010, ApJ, 720, 694

Papish, O., & Soker, N. 2011, MNRAS, 1321

Sneden, C., Roederer, I., Cowan, J., & Lawler, J. E. 2010, Nuclei in the Cosmos.,

Smith, N., Cenko, S. B., Butler, N., et al. 2011, arXiv:1108.2868

Soker, N. 2010, MNRAS, 401, 2793

Volk, K., & Kwok, S. 1985, A&A, 153, 79

Wang, L., Howell, D. A., Höflich, P., & Wheeler, J. C. 2001, ApJ, 550, 1030

Wilson, J. R., Mayle, R., Woosley, S. E., & Weaver, T. 1986, Annals of the New York Academy of Sciences , 470, 267

Witti, J., Janka, H.-T., & Takahashi, K. 1994, A&A, 286, 841

Woosley, S. E., & Hoffman, R. D. 1992, ApJ, 395, 202

Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229

Woosley, S., & Janka, T. 2005, Nature Physics, 1, 147

This preprint was prepared with the AAS LaTeX macros v5.2.